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# Probabilistic model for multi-axial dynamic load combinations for wind turbines

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ABSTRACT

The article presents a model describing the joint probability distribution of multiple load components acting on a wind turbine blade cross section. The problem of modelling the probability distribution of load time histories with large periodic components is addressed by dividing the signal into a periodic part and a perturbation term, where each part has a known probability distribution. The proposed model shows good agreement with simulated data under stationary conditions, and a design load envelope based on this model is comparable to the load envelope estimated using the standard procedure for determining contemporaneous loads. Using examples with simulated loads on a 10 MW wind turbine, the behavior of the bending moments acting on a blade section is illustrated under different conditions. The loading direction most critical for material failure is determined using a finite-element model of the blade cross section on which load combinations with different directions but with equal probability are applied. By defining a joint probability distribution and return-period contours for multiple load components, the suggested procedure is applicable to different aspects of the design of wind turbine blades, including the possibility for carrying out reliability analysis on an entire cross section.

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## 1. Introduction

Wind turbines as moving machinery subjected to random environmental influence experience loads and deformations along multiple degrees of freedom in the structure. A fully three-dimensional detailed stress analysis of the entire structure under dynamic loading is extremely expensive computationally. Therefore, the dimensioning of the wind turbine structure is usually based on design loads, which are estimated by dynamic finite element or modal simulations using a simplified representation of the structure in terms of beam elements. In this case, the design loads represent dynamic load effects caused by external aerodynamic and electromechanical loads in combination with inertia, and are specified in terms of internal forces and moments in the degrees of freedom available in a beam finite-element model. Since each node in a three-dimensional beam element has six degrees of freedom, any given load condition at a beam node, i.e., a cross section of a turbine component, will be a combination of six load components. Due to the non-symmetric geometry of some of the turbine components such as the blades, using only the vector magnitude of the loads is not sufficient as the maximum allowable loads will vary for different load directions. The design of a wind turbine blade thus needs to be based on load combinations where the combined effect of loads in different directions is taken into account. In current wind turbine design guidelines (i.e., IEC 61400-1, ed.3 from 2005 [1]) the problem of finding the contemporaneous values of different load components is addressed in a relatively simple way by considering the extreme loads in one direction at a time; the contemporaneous values for loads in other directions are considered equal to their respective mean values. Similarly, scientific literature offers numerous studies on statistical load extrapolation, however in these studies the load components are considered independently from each other [2–4]. To the knowledge of the authors, methods for estimating the actual joint probabilities of wind turbine loads in multiple directions are not available in literature. The present study demonstrates a multivariate model for the joint probability distribution of contemporaneous extreme loads on wind turbines. The model considers the load components as a combination of a cyclic, gravity-driven component and a randomly distributed perturbation. The subtraction of the sinusoidal signal from the random data results in better possibilities for assessing the correlations between loads in different directions, and thus leads to an improved model for the joint distribution of loads. The parameters of the marginal distributions are estimated from dynamic simulations of the wind turbine behavior under turbulent incoming wind. The joint distribution of the perturbations in

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different directions is obtained from the marginal distributions using the Nataf multivariate transformation [5], or a Rosenblatt transformation [6]. A joint distribution for the loads is then obtained by convolution of the sinusoidal signal with the perturbations and integration over the rotor azimuth angles. An example application of this distribution model is to define the return period contours for extreme load combinations and thus the design load envelope, but it also gives the possibility for carrying out reliability analysis of wind turbine components. In the present paper, the multiaxial load model is used to analyze the load effects on the blades of a 10 MW reference turbine. Furthermore, an example application is presented for determining the most critical loading direction for a blade cross section by subjecting the section to loads with equal probability with varying direction.

## 2. Extreme loads from aeroelastic simulations

### 2.1. Input description

The loading state considered in this work is the multi-axial extreme load acting on a cross section from a wind turbine blade. For the purpose of the study the Technical University of Denmark's (DTU) 10 MW reference wind turbine model [7] with rotor diameter of 179 m and hub height of 119 m is used. The loads are determined from aeroelastic simulations using the Hawc2 code [8]. Fitting a representative probabilistic model of the loads is only feasible under stationary conditions, i.e., constant mean wind speed, turbulence, etc., and if long-term load distributions under varying conditions are required, they are normally estimated by fitting a number of short-term distributions under stationary conditions, followed by integration over the respective distribution of long-term variables [4,1,9]. For simplicity we consider stationary time series with a fixed mean wind speed of 11 m/s, turbulence intensity 0.176 (IEC turbulence class B), and wind shear exponent of 0.2. Another factor with an influence on the stationarity of the loads is the blade pitch angle. An increase in the pitch angle normally leads to a reduction in the aerodynamic thrust acting on the rotor, and hence to reduction in the flapwise loads. In the following, the analysis methods are first presented by addressing only the time periods in the simulations when the blade pitch angle is nearly zero (less than 0.5°). This can be considered as a worst-case scenario since the thrust force over the rotor and hence the bending moments acting on the blades are highest at zero pitch angle and 11 m/s is the wind speed at which the highest extreme loads are typically attained. This set of conditions is sufficient for demonstrating the methods for modelling of the joint distribution of extreme loads. Afterwards, Section 4 demonstrates an example of how the change in pitch angles can be accounted for, and the resulting effect on the load distribution. In principle, when using an extreme load probability distribution for design purposes it will be necessary to fit a number of short-term distributions under different wind conditions and take account of different blade pitch angles, and then estimate the design load envelope by integrating the short-term distributions into a long-term distribution.

### 2.2. Extraction of load extremes

The ultimate limit state design loads for a wind turbine are specified as the extreme loads with a given long period of recurrence (i.e. 1 year or 50 years). Considering that the load time series represent a sampled continuous random process, the long-term extremes are expected to follow an extreme-value distribution which is related to the distribution of the local peaks of the random process [10,4]. The so-called short-term distribution of peaks with respect to a specific reference period, $T$, is obtained by raising the local distribution to the power $n(T)$, where $n$ is the expected number of load peaks within one time period $T$:

$$F_{short-term}(M|\boldsymbol{\theta},T) = [F_{local}(M|\boldsymbol{\theta})]^{n(T)} \tag{1}$$

where $\boldsymbol{\theta}$ is a vector of input variables that define the statistical distribution of the extremes (e.g., blade pitch angle, mean wind speed, turbulence, wind shear), $T$ is the observation time period, $M$ is the magnitude of the extreme load, and $n(T)$ is the number of independent local extremes considered per one time period $T$. For a stationary process with mean upcrossing rate $\nu_m, n(T) = \nu_m T$. For example, if the desired reference time period is $T = 10$ min (the typical duration of a single aeroelastic simulation), $n(T)$ equals the number of load peaks extracted per one time series realization. Integrating the short-term distribution over the multi-dimensional domain of input variables, $\boldsymbol{\theta} = [\theta_1, \theta_2, \dots, \theta_m]$, results in the so-called long-term distribution:

$$F_{long-term}(M \mid T) = \int_{\boldsymbol{\theta}} F_{local}(M \mid \boldsymbol{\theta}, T)^{n(T)} f(\boldsymbol{\theta}) \mathrm{d}\boldsymbol{\theta} \tag{2}$$

The local distribution of peaks may be characterized in terms of the process crossing rates or statistical moments [11,10]. However, this will often require a large amount of time series unless an assumption about the distribution of the random process or the distribution of the local peaks is made [10]. Since the load extremes distribution is the quantity of interest in the present case, it is convenient to directly fit a distribution to the set of independent load extremes extracted from a time series under consideration. In the multivariate case however, the definition of an extreme event is more complicated as all related load components have to be taken into consideration. The author adopts an approach where a point in time $t = \tau$ is considered a load peak if it satisfies the following two conditions:

(1) There is a load reversal of $M_{x0}$ or $M_{y0}$ at $t = \tau$, i.e.,

$$\begin{aligned} &M_{x0}(\tau) \geqslant M_{x0}(\tau - \Delta t) \quad \text{and} \quad M_{x0}(\tau) \geqslant M_{x0}(\tau + \Delta t) \\ &\quad \text{(positive reversal)}, \text{ or} \\ &M_{x0}(\tau) \leqslant M_{x0}(\tau - \Delta t) \quad \text{and} \quad M_{x0}(\tau) \leqslant M_{x0}(\tau + \Delta t) \\ &\quad \text{(negative reversal)} \end{aligned}$$

and analogically for $M_{y0}$:

$$\begin{aligned} &(M_{y0}(\tau) \geqslant M_{y0}(\tau - \Delta t) \quad \text{and} \quad M_{y0}(\tau) \geqslant M_{y0}(\tau + \Delta t)), \text{or} \\ &(M_{y0}(\tau) \geqslant M_{y0}(\tau - \Delta t) \quad \text{and} \quad M_{y0}(\tau) \geqslant M_{y0}(\tau + \Delta t)) \end{aligned}$$

(2) There is no larger peak within 3s before and after $t = \tau$, e.g.,

$$\max_{M_{x0}(t)} (t \in [\tau - 3s, \tau + 3s]) = M_{x0}(\tau).$$

In the above, $M_{x0}$ denotes the flapwise bending moment, and $M_{y0}$ the edgewise bending moment acting on a blade cross section, where the edgewise and flapwise directions correspond respectively to the $x$- and $y$-axes in a blade-reference coordinate system (e.g., Fig. 13). For a blade pitch angle equal to zero, the edgewise direction is parallel to the rotor plane, while the flapwise direction is perpendicular to it. The blade coordinate system rotates with the pitch angle, so the loading directions are fixed with respect to the section geometry. However, as changing the blade pitch angle influences the aerodynamic loads, the distribution of $M_{x0}$ and $M_{y0}$ will change for different pitch angles. The choice of 3 s separation between peaks means that at the turbine's rated speed of 1 rad/s, successive peak events will be separated by at least half a rotor revolution, which reduces the possibility that the peaks are correlated. The subscript 0 in $M_{x0}$ and $M_{y0}$ is introduced to distinguish between the original time series and the peaks extracted from

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